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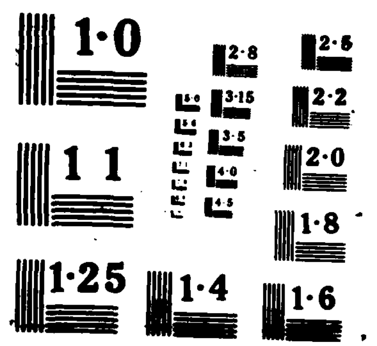
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FOREIGN TECHNOLOGY DIVISION

ON ROLLING RESONANCE AND SLIGHTLY ASYMMETRICAL AERODYNAMIC FORCE OF THE REENTRY BODY

by

Cai Jinshi

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HUMAN TRANSLATION

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ON ROLLING RESONANCE AND SMALL ASYMMETRICAL AERODYNAMIC FORCE OF RE-ENTRY BODY

Cai Jinshi

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Abstract

In this paper, the problem in flight mechanics and aerodynamics for rolling resonance of the re-entry body, ~~are discussed~~, the mechanism of divergence of angle of attack of the re-entry body is also analysed. It is shown that rolling resonance is a primary hazard of the re-entry body in the divergence of angle of attack. Research results of the re-entry body in rolling resonance and small asymmetrical aerodynamic force as well as existential problems are emphatically described. It indicates that ~~to~~ determine random ablative configuration and corresponding mathematical expectation and variance of small asymmetrical aerodynamic coefficients are key problems on predicting the rolling resonance probability which the re-entry body occurs, whereas ~~flight test~~ is the primary way to solve this difficult problem.

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ON ROLLING RESONANCE AND SLIGHTLY ASYMMETRICAL AERODYNAMIC FORCE OF THE REENTRY BODY

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This paper discusses the problems in flight mechanics and aerodynamics for rolling resonance of the reentry body; the mechanism of divergence of angle of attack for the reentry body is analyzed. It is pointed out that rolling resonance is the primary hazard for divergence of angle of attack of the reentry body. This paper concentrates on the description of research results of problems of the reentry body in the rolling resonance and slightly asymmetrical aerodynamic force as well as existing problems.

In the early 60's, there were phenomena of rolling abnormality and divergence of angle of attack, which were not supposed to happen to a symmetrical flight vehicle, in reentry flight tests. In 1960, the British BK-9 reentry body[1] had divergence of angle of attace at low altitude and the body disintegrated; in 1966, the American MK-12 warhead also experienced destruction incidents during the reentry process; in 1975, the MK-400 had excessive lateral overload phenomenon. The occurrences of these incidents and phenomena caused great concern among the researchers of flight mechanics and aerodynamics. In the past twenty years or so, the rolling abnormality and divergence of angle of attack of reentry bodies and other related aerodynamic problems have become one of the most important subjects in the research field of aerodynamics and flight mechanics. This paper discusses this problem and analyzes the mechanism of divergence of angle of attack during reentry process and the primary hazard of divergence of angle of attack for slender reentry bodies and concentrates on the description of research development of the reentry body in rolling resonance and slightly asymmetrical aerodynamic force as well as problems to be solved.

I. Mechanism of Divergence of Angle of Attack

The oscillatory motion of angle of attack for a symmetrical reentry body with slightly asymmetrical configuration can be approximated as a second-order linear oscillatory system under the effects of external forces. The motion is composed of three modes, i.e. perturbational mode, nutational mode, and trim mode[2]. Due to differences in the nature of characteristic roots of the equation for oscillatory motion of angle of attack, four types of divergence of angle of attack are formed[3] (see Fig. 1):

1. Nonperiodic Instability. Nonperiodic instability of angle of attack occurs when the two characteristic roots of the second-order, equal-power equation of angular motion of the reentry body are both positive real numbers.

The reentry body is also designed to be statically stable. But when the reentry body enters the transitional region of the boundary layer, the asymmetrical transition of boundary layer and mass addition to boundary layer by ablation can make the pressure center shift forward,[4,5] and possibly cause nonperiodic instability. This factor should be considered in the design to leave sufficient static stability tolerance. For the reentry body with a nosetip of carbon-based ablative material, its amount of ablation is small and the amount of pressure center forward shift can be omitted.[6] The possibility of the reentry body's being nonperiodically unstable, which is caused by ablation, is small.

2. Oscillatory Instability. Oscillatory instability of angle of attack occurs when the two characteristic roots of the second-order, equal-power equation of angular motion of the reentry body are both complex variables with both real parts being

positive. The real part of the characteristic value is determined by normal force derivative, kinetic pressure gradient and damping moment derivative of these three factors. For the reentry body, both the normal force and kinetic pressure gradient have damping effects[7]; therefore, only when the damping moment derivative is a larger positive number, can oscillatory instability result.

During the reentry process, the mass addition to the boundary layer caused by ablation of the reentry body has specific effects on the damping moment derivative. During flight tests[7] and three-degree-of-freedom kinetics balance experiments of the free-flight ballistic target[8] and the regular hypersonic wind tunnel, the positive value of damping moment derivative causing mass addition have been observed; similar results[10,11] have also been obtained by theoretical calculations. The experimental and calculated positive value of damping moment derivatives are both of the order of magnitude of 1, and they are far smaller than the kinetic pressure gradient damping effect; the latter corresponds with the normal force and kinetic pressure gradient damping effect, and therefore oscillatory instability does not threaten the reentry body too much.

3. The Magnus-type kinetic Instability. Perturbational instability or nutational instability occurs when the two characteristic roots are complex variables with one having a positive real part and the other having a negative real part, and they are each called Magnus-type kinetic instability.

The Magnus-type aerodynamic moment is the moment whose value is proportional to the angle of attack and whose azimuth is perpendicular to the pitching moment, i.e. the so-called "plane external moment". It makes the damping of one oscillatory mode of angle of attack increase, whereas the damping of the other mode decreases. When this moment is large enough, it will result in Magnus-type instability.

From the analysis of reentry body flight test data, the following has been obtained: the Magnus type moment can be generated from

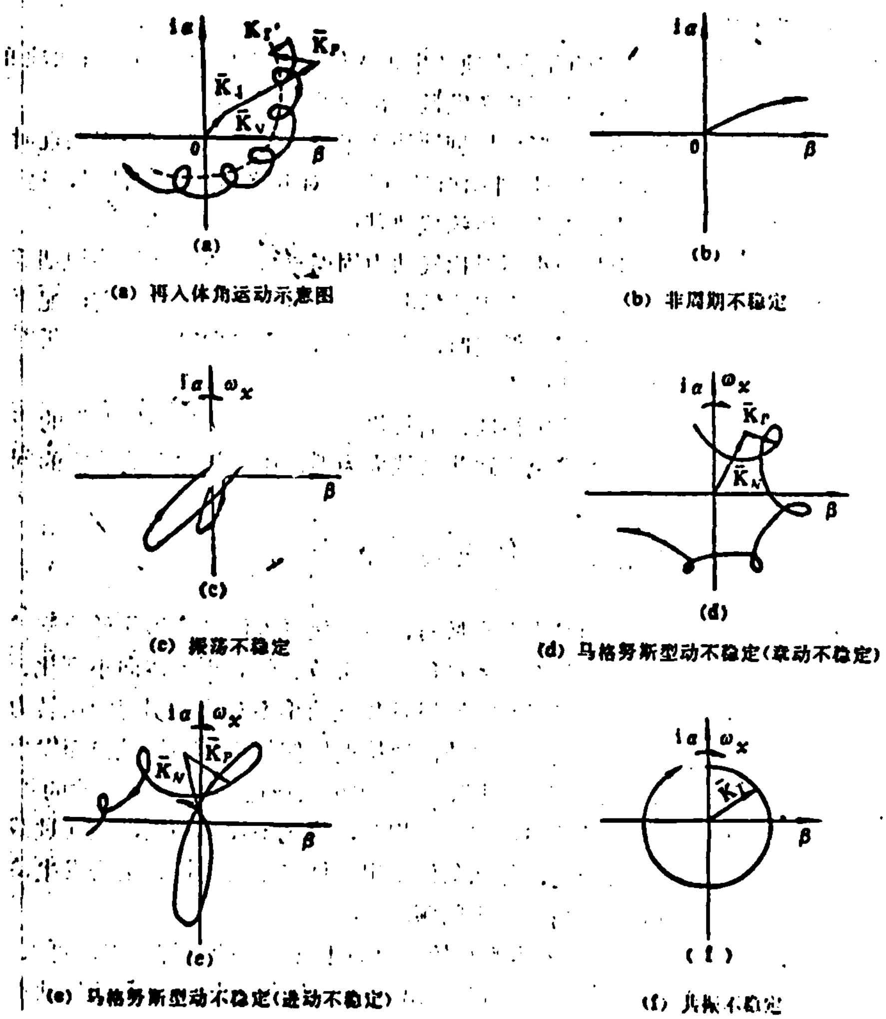

Fig. 1 Basic types of divergence of angle of attack of warheads.
Key: (a) Schematic diagram of reentry body's angular motion; (b) nonperiodic instability; (c) oscillatory instability; (d) Magnus-type kinetic instability (nutational instability); (e) Magnus-type kinetic instability (perturbational instability); (f) resonance instability

boundary layer asymmetrical transition[12,13] and ablative thermal lag[1]. It has also been observed from the force measuring test of a regular hypersonic wind tunnel, low temperature ablation, that there is Magnus-type aerodynamic force[14] when angle of attack is larger, and this indicates that the rotating warhead which is being ablated will indeed generate the Magnus-type aerodynamic force and moment. However, when the rolling velocity is smaller, the Magnus-type moment is also smaller, and only when the rolling velocity approaches the natural frequency of pitching vibration or far greater than this frequency can the Magnus-type instability occur.[3] Therefore, as long as the rotational velocity is controlled to be smaller than the pitching frequency, the occurrence of the Magnus-type instability can be avoided.

4. Resonance Instability. The unequal-order terms of the angular motion equation generate the trim angle of attack of the reentry body. When the oscillatory frequency of the unequal-order terms approaches the inherent frequency of the equal-order terms, the trim angle of attack diverges and resonance instability occurs.

The pressure pulses upon transition of the re-entry body boundary layer form periodic external forces. When the latter approaches the pitch rate, then resonance instability[15] results, and its trim angle of attack peak value is related to the induced quantity of ablation. For carbon-based, low ablative material, the trim angle of attack value caused by this kind of resonance instability is smaller and presents very little threat to the reentry body.

The slightly asymmetrical aerodynamic force caused by the slightly asymmetrical configuration of the reentry body is firmly attached to the reentry body and its oscillatory period is equal to the rolling speed. Rolling resonance appears when the rolling velocity approaches the pitching inherent frequency, and resonance instability of angle of attack occurs; the trim angle of attack will increase vastly and the lateral overload will also increase vastly. When resonance appears at low altitude, the reentry body could snap due to excessive lateral overload. According to reports, the American MK-12 was destroyed due to rolling resonance.

As the reentry body develops in the direction of miniaturization, reducing static stability tolerance and slenderization, the greater the probability is for rolling resonance to occur. Therefore, how to adopt effective measures to prevent rolling resonance has become a problem of significant importance in designing the reentry body.

II. Study of Rolling Resonance of the Reentry Body

In order to maintain stable flight outside the atmosphere and reduce the scattering of touchdown location, the reentry body is generally made to spin around the longitudinal axis at a low spinning speed. Large reentry bodies of early years had little change in their rolling speeds which remained close to constant during the entire reentry process. As the reentry body develops in the direction of miniaturization, small static stability and a high ballistic coefficient, the effects on change of rolling speed by rolling moment generated from the mass, inertia, and aerodynamic slight asymmetry also grow larger and larger, and it is possible to make rolling speed at low altitude approach pitching frequency (critical rolling speed) thereby resulting in rolling resonance,[16] or even parametrical resonance,[17] subharmonic and resonance[18-20] and circular limit motion.[21] The most dangerous situation is to have roll-pitch lock-in phenomenon happen, i.e. the rolling speed approaches pitching frequency for a longer period of time causing the trim angle of attack to increase and lateral overload to increase vastly, thereby resulting in disintegration of the reentry body. Of primary concern in designing are three questions: under what condition will low altitude rolling resonance appear, whether or not roll-pitch lock-in will occur, and how large a trim angle of attack will roll-pitch lock-in cause.

1. Conditions for low altitude rolling resonance: usually the initial rolling speed of a reentry body is higher than the pitching frequency at the reentry point. During the reentry process, the pitching frequency increases rapidly. At 30 or so kilometers, the two are equal and the first rolling resonance (high altitude rolling resonance) appears. But the slight asymmetry and kinetic pressure of the reentry body are both small at this time and the change in rolling speed cannot catch up

with the change in the rapidly rising pitching frequency. Usually instantaneous rolling resonance will appear, but it has little effect on overload of the reentry body. Afterward, the rolling speed of the reentry body continues to change under the effect of small asymmetry. If the reentry body's amount of small asymmetry is very small, then the change in rolling speed is small and rolling resonance will not occur again at low altitude; only when the amount of slight asymmetry is sufficiently large to make the rolling speed of the reentry body increase rapidly and accelerate to be equal to the pitching frequency of the reentry body before touchdown, can low altitude rolling resonance appear (see Fig. 2). Then, how large an amount of slight asymmetry is required exactly in order to have low altitude rolling resonance appear? Of course, this can be determined through large amounts of six-degree-of-freedom ballistic numerical calculation. But what is more significant in preliminary design is to give analytical relations, i.e. an analytical solution of rolling speed. It can be used to approximately estimate the probability for the reentry body to have rolling resonance. There has been some work done in this area.

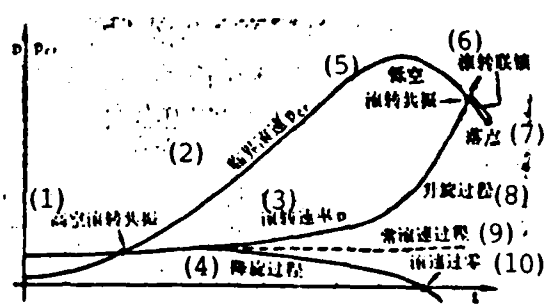

Fig. 2 Schematic diagram of rolling resonance and rolling speed passes zero.
Key: (1) High altitude rolling resonance; (2) critical rolling speed; (3) rolling speed; (4) descending rotational process; (5) low altitude rolling resonance; (6) roll-pitch lock-in; (7) touchdown point; (8) ascending rotational process; (9) constant rolling speed; (10) rolling speed passes zero.

W.J. Bootle[22] omitted the aerodynamic asymmetry to obtain an analytical solution when only inertial slight asymmetry was present. Since the effects of aerodynamic asymmetry on tolling speed is proportional to $1/(1-\lambda^2)$, and the effects of inertial slight asymmetry on rolling speed is proportional to $\lambda^2/(1-\lambda^2)$ (λ is the ratio of rolling speed to critical rolling speed), the effects of inertial slight asymmetry on rolling speed are only significant in adjacent resonance regions, the effects of aerodynamic asymmetry and mass center shift on the change of rolling speed are far greater than those of the inertial asymmetry during the entire reentry process. The author[23] had omitted the inertial slight asymmetrical effects to obtain analytical solution for rolling speed at constant aerodynamic and mass slight asymmetry. D. Siegelmen, et al[24] also obtained the rolling speed integration expression with inertial slight asymmetry omitted. The expression contains unknown functions of various amounts of slight asymmetry which change with density, thus are not convenient for engineering application. The author[25] derived, under the assumption that the amount of aerodynamic slight asymmetry induced by ablation-erosion of the reentry body is proportional to the amount of backward shift of the reference point, the relationship between the slight asymmetrical aerodynamic force and motion parameters of the reentry body and obtained the rolling speed expression when the slight asymmetrical aerodynamic force is a variable; the author also gave the conditions and probability estimation for the reentry body to have low altitude rolling resonance, taking the change of small asymmetrical aerodynamic force along the reentry process and its asymmetrical coupling effects with mass into consideration. However, further research is required to simultaneously consider low altitude rolling resonance conditions of inertia, mass and aerodynamic slight asymmetry.

2. Criterion for roll-pitch lock-in: the motion conditions of massive increase in the trim angle of attack and lateral overload caused by the rolling speed of the reentry body's being close to the critical rolling speed for a long period of time is called roll-pitch lock-in. Based on the above definition, only when rolling acceleration is equal to or greater than the rate of critical rolling speed change can roll-pitch lock-in possibly occur.

The criterion for roll-pitch lock-in is usually expressed as the product of the trim angle of attack at zero rolling speed and the amount of lateral shift of center of gravity-center of pressure. Migotsky[26], under the condition of linear trajectory and density changing with the index, included resistance and pitching damping effects to obtain the criterion for roll-pitch lock-in. Bootle[27] omitted the resistance effect and, using the trim angle of attack asymptotic formula of Kanno,[28] also obtained similar criterion for roll-pitch lock-in. Glove[29] further researched the effects of rolling damping and pure rolling moment on lock-in and pointed out that rolling damping has an unlocking effect on the lock-in, and gave the rolling damping value required to unlock roll-pitch lock-in under known conditions; research results indicate that the pure rolling moment enhances the lock-in when it is of the same sign with initial rolling speed; otherwise it unlocks the lock-in. The aforementioned results are all based on stable trim theory and the conclusions tend to be conservative.

It is observed from the criterion for roll-pitch lock-in that the smaller the parameters such as re-entry body dimension (D), weight resistance ratio (W/C_DS), width length ratio (D/L, I_x/I_y), static stability tolerance (η), mass distribution factor (I_y/mD^2), kinetic stability derivative (C_{mq}), ballistic inclination angle (θ), kinetic pressure corresponding rate of change ($\dot{q}/q$), etc. are, the larger the probability for roll-pitch lock-in is. It should be especially pointed out that the criterion for roll-pitch lock-in is proportional to the square of flight vehicle dimension and the static stability tolerance, whereas the amount of slight asymmetry does not decrease in square proportion to the reduction in the flight vehicle's dimension. Therefore, the smaller the reentry body is, the greater the danger of having roll-pitch lock-in is.

3. The trim angle of attack: when sustained rolling resonance occurs, the lateral overload subjected by the reentry body is proportional to the trim angle of attack. Therefore, peak value of the trim angle of attack at resonance is the key parameter crucial to the survival of the reentry body.

As early as the 50's, Nicolaides[2] showed the solution of stable trim angle of attack for a slightly asymmetrical body; in the 60's, Kanno[28] obtained, under the assumption of linear trajectory, constant flight velocity, constant rolling speed and density changing with index, the analytical solution of stable trim angle of attack with mass and aerodynamic slight asymmetry taken into consideration. In the 70's, Hodapp[30-34] again analyzed the effects of various amounts of slight asymmetry on stable trim angle of attack in detail; and using the six-degree-of-freedom ballistic simulation calculation, he verified the stable trim value, studied the effects[32] of inertial asymmetry caused by shifting of the inertial main axis on the stable trim angle of attack and found that the stable trim angle of attack generated by mass and aerodynamic slight asymmetry in the sub-resonance region (rolling speed is smaller than the critical rolling speed) is greater than the corresponding stable trim angle of attack generated by inertial slight asymmetry; whereas the reverse is true in the super-resonance region. He pointed out,[33] after studying the effects of asymmetrical static derivative on stable trim angle of attack, that the asymmetry of static derivative ($m_z^{\alpha} \neq m_y^{\beta}$) will increase the stable trim angle of attack. Lastly, he also studied the effects[34] on the trim angle of attack when the inertial product is not zero, and pointed out that the effects of the inertial product is only limited in the resonance point domain. Ingram[35] studied the effects of asymmetrical damping derivative on the trim angle of attack. He thought the assumption ($m_z^{\omega}z=m_y^{\omega}y$) made him underestimate the value of the trim angle of attack. The aforementioned results are all obtained under the assumption of constant rolling speed. The oscillatory component of the trim angle of attack obtained is greater than the true value of the trim angle of attack. Since rolling speed changes rapidly near the resonance point, there is a discrepancy between the true value of trim angle of attack and the stable trim angle of attack for the reentry body, and this discrepancy is related to the aerodynamic pitching frequency of the reentry body; the higher the inherent pitching frequency of the reentry body, the quicker the response of the reentry body is and the smaller the discrepancy. Glove[29] used the six-degree-of-freedom simulation calculation to study the applicable range of the aforementioned trim theory and pointed out afterward that: the roll-pitch lock-in conditions given by the trim theory are too stringent and the stable trim angle of attack is too large; only when the rolling enlargement factor is smaller than 10~20 can the roll-pitch conditions and analytical solution for the trim angle provided by the trim theory be applied. Therefore, the analytical solutions which take into consideration changing process of rolling speed, responding characteristic criterion for roll-pitch lock-in of the reentry body, and the trim angle of attack, still require further study.

III. Amount of Slight Asymmetry of the Entry Body

Whether or not sustained roll-pitch lock-in occurs for a reentry body is determined by the coupling effect of mass slight asymmetry, inertia slight asymmetry and aerodynamic slight asymmetry (see Fig. 3). Part of the amount of these slight asymmetries comes from factors such as machining, installation discrepancies, etc., but the majority are still caused by the ablation, erosion and boundary layer transition of the reentry process. Obviously, the amount of these small asymmetries is related to random quantities such as machining discrepancies, external interference, material characteristics, and meteorological conditions, etc., and cannot be accurately determined. However, for the reentry body under specific conditions, the amount of these slight asymmetries still has its specific mathematical expectation and variance. Determining the mathematical expectation and variance of the amount of these small asymmetries is the key problem in solving rolling resonance of the reentry body.

1. Mass and inertia slight asymmetry: mass slight asymmetry means the amount of lateral shift of the mass center with respect to the longitudinal axis of the reentry body. It is primarily caused by machining and installation discrepancies, and these discrepancies can be measured before shipping the products. The effects of lateral shifting amounts of the aerodynamic center of pressure with respect to the longitudinal axis of the reentry body

on rolling resonance are the same as the effects of lateral shifting amounts of center of mass on rolling resonance. Therefore, the mass asymmetry is usually expressed using the projected distance r_{GP} between centers of pressure and mass on the cross-section of the reentry body.

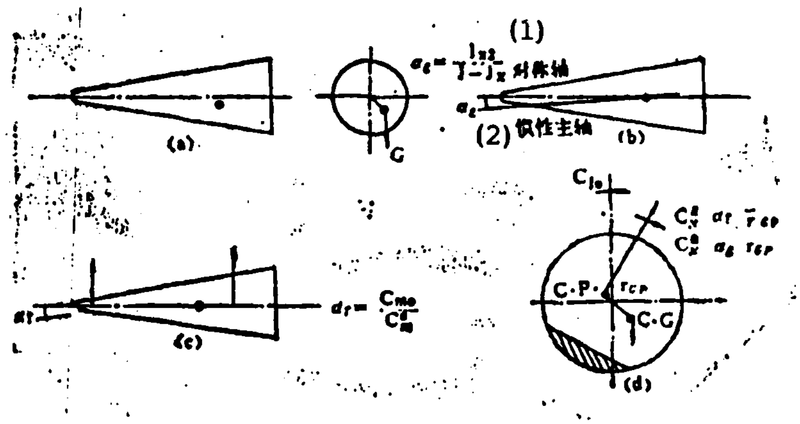

Fig. 3 Schematic diagram of the amount of slight asymmetry of the reentry body.
(a) mass asymmetry; (b) inertial asymmetry; (c) aerodynamic asymmetry; (d) coupling effect of various amounts of slight asymmetry.
Key: (1) axis of symmetry; (2) inertial main axis.

The amount of shift of the center of pressure due to ablation is very small and is difficult to obtain from wind tunnel experiments and numerical calculation. The author[36] adopted the maximum approximation method and provided a calculating method whereby the lateral shifts of the centers of pressure and mass of the reentry body can be directly obtained from angular velocity of flight tests and overload data.

The inertial asymmetry means that the inertial product of the reentry body is not zero. It is primarily caused by machining and installation discrepancies, and it is difficult to measure before shipping. Glove[39] omitted the aerodynamic effects during high altitude flight to obtain the method for determining the inertial product from angular velocity data of the reentry body.

2. Zero angle of attack recovery moment coefficient: the zero angle of attack recovery moment coefficient $\bar{C}_{m0}$ is the aerodynamic recovery moment coefficient of the symmetrical reentry

body formed at zero angle of attack due to slightly asymmetrical configuration. $\bar{C}_{m0}$ caused by inclination and bending of the reentry body axial line due to factors such as machining, installation, etc., is relatively small, and its order of magnitude can be estimated through assuming the maximum inclination angle and the flexure of the reentry body's longitudinal axis and using the Newtonian theory[29] or two-line model;[37] $\bar{C}_{m0}$ due to ablation is primarily caused by asymmetrical ablation of the nosetip of the reentry body. $\bar{C}_{m0}$ can be obtained through numerical calculation, wind tunnel experiments and flight tests as long as the slight asymmetrical configuration is given.

Hahn[38] obtained the pitching moment coefficient through a static force measuring experiment in a regular wind tunnel, and its value at zero angle of attack is $\bar{C}_{m0}$. However, since this quantity is very small, higher measurement accuracy is required; $\bar{C}_{m0}$[39] can also be obtained from stable trim angle through experiment using three-degree-of-freedom kinetics balance in a regular wind tunnel. Swain used the modified Newtonian theory or blunt cone pressure interrelationship and approximation formula of effect of the nosetip on downstream to give the approximation calculating method of aerodynamic moment coefficient for the reentry body with slightly asymmetrical nosetip, and thereby obtaining $\bar{C}_{m0}$.[40] Hall et al. gave the method of nonviscous numerical computation for slightly asymmetrical aerodynamic forces of configuration of an ablative nosetip.[41,42] Rize[43] recently used the unsteady thin layer N-S equation stable computational method and took viscous-nonviscous interference into account to obtain numerical solutions for asymmetrical ablative nosetip and supersonic regions, and the slightly asymmetrical recovery moment coefficient can also be obtained. Hence, the key problem in obtaining slightly asymmetrical aerodynamic forces of the reentry body is to determine the slightly asymmetrical configuration of the nosetip.

Typical ablative configuration for nosetip during the reentry process includes laminated flow type, transitional type, indentation type and equilibrium turbulent flow type. The mechanisms are different for various types of asymmetrical ablation. The laminated flow type asymmetrical nosetip is mainly caused by the reentry body initial angle of attack's not being zero. Research by Platus[44] has indicated that the reentry motion always causes the initial amount of slight asymmetries to decrease; therefore, the amount of slight asymmetry of the laminated flow type is relatively small. Currently, the commonly used carbon-carbon asymmetrical indentation type and equilibrium turbulent flow type nosetips are primarily caused by the random distribution of ablative roughness of surface laminated flow.[45] Based on this point, Dirling used the probability distribution density of laminated flow ablative roughness of the ATJ-S graphite ablation model to build a statistical model for calculating the ablative configuration, [46,47] and calculated the zero angle of attack recovery moment coefficient $\bar{C}_{m0}$ and the corresponding trim angle of attack for this kind of slightly asymmetrical configuration. The maximum and minimum values of the obtained trim angle of attack are compared with the flight test results, and their order of magnitude is consistent (see Fig. 4).

The other way of determining the slightly asymmetrical ablative nosetip configuration is to conduct low temperature ablation experiments in the wind tunnel [48,49] and pressure-increase (Ramp) experiemtns on the heating device. [50,51] In addition, Hall et al. proposed [41,52] the use of flight tests to obtain aerodynamic coefficients C_m, C_N and C_A and the backward shift of ablation of several points on the nosetip and the method for identifying slightly asymmetrical nosetip configuration in order to obtain configuration change of the reentry body along the trajectory. Information such as backward shift of ablation, overload, etc. of flight tests and the resistance experiments of a series of candidate slightly asymmetrical models can also be used to identify the slightly asymmetrical nosetip configuration.[53] A more direct method is from the angular velocity and overload field measurement data of flight tests to directly obtain the slightly asymmetrical aerodynamic coefficients of the reentry body.[54,55,36]

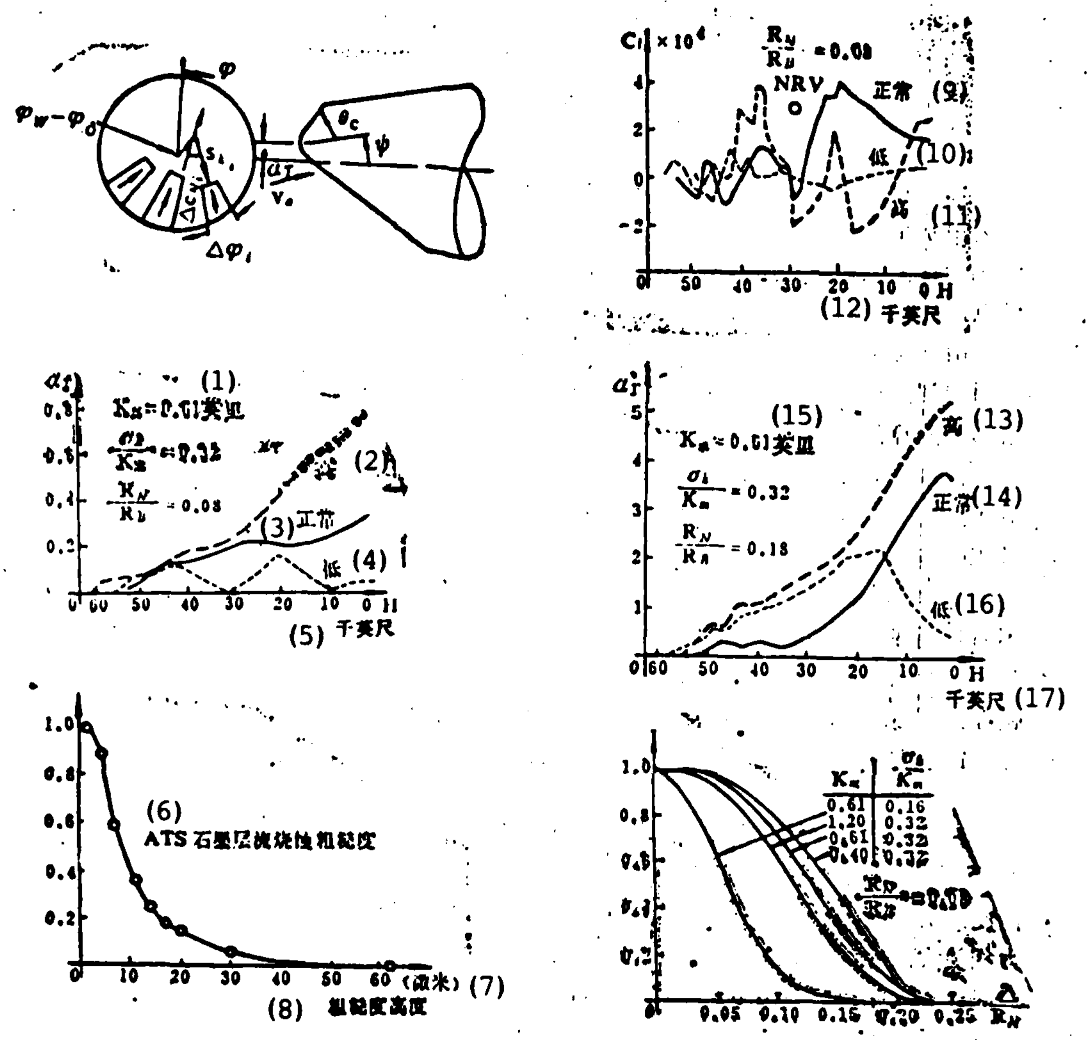

Fig. 4 Calculated results for the random model of ablative configuration
Key: (1) mile; (2) high; (3) normal; (4) low; (5) thousand feet; (6) ATS graphite laminated flow ablative roughness; (7) micrometer; (8) height of roughness; (9) normal; (10) low; (11) high; (12) thousand feet; (13) high; (14) normal; (15) mile; (16) low; (17) thousand feet.

3. Pure rolling moment coefficient $C_{\ell 0}$: the forming mechanism of $C_{\ell 0}$ is different from that of $\bar{C}_{m0}$-- it is primarily caused by large surface ablation of the reentry body. It can be observed from the low temperature ablation experiments of the wind tunnel that when the model is in rotational motion, the ablation patterns of the cone surface are in a spiral shape, thereby forming $C_{\ell 0}$.[56,57] For strip-wrapping type (carbon phenolic aldehyde) heat shield,

the mechanism that produces $C_{\ell 0}$ is different from the low temperature ablation model. Primarily, it is because the strip edge where the carbon phenolic aldehyde strips connect to each other is exposed to aerodynamic rolling moment in the ablative environment, which is similar to the aerodynamic slight asymmetry that generates rolling moment; the nonuniformly formed ablation spiral patterns of the wrapping strips can also produce rolling moment. Therefore, the wrapping method (including connecting method, wrapping direction, amount of overlapping, etc.) and spacing of wrapping have greater influences on $C_{\ell 0}$.[58] In order to study the effects of these parameters on pure rolling moment, the U.S. conducted pure rolling moment experiments for more than 150 models on a 50 MW electric arc heater.[58-61] Larmour[62] proposed the use of different wrapping methods to conduct passive control of rolling speed. In order to verify this idea, the Sandia Laboratory manufactured the pure rolling moment estimation large net (RTE) [63] and conducted systematic flight tests using the TATER rocket to simulate actual trajectory and accurately obtained the pure rolling moment coefficient of carbon phenolic aldehyde wrapping in an ablative environment. Through testing, effects on pure rolling moment by factors such as left-right wrap-overlapping, weaving method, up-down connecting, fiber length, etc., have been better understood.

Conclusions

Rolling resonance is one of the primary threats which a small, slender reentry body might encounter during the reentry process. For a specific reentry body, studying and determining the mathematical expectation and variance of slightly asymmetrical aerodynamic coefficients $\bar{C}_{m0}$ and $C_{\ell 0}$ are the key problems in predicting occurence probability of rolling resonance. The key to solving this problem lies in the determination of random ablative configuration.

At present, the criterion for roll-pitch lock-in and the trim angle of attack are based on the stable trim theory, which is relatively conservative. It is necessary to further study the effects of rolling speed change process and responding characteristics of the reentry body on the criterion for roll-pitch lock-in and the trim angle of attack as well as simultaneously taking the low altitude rolling resonance conditions of mass, inertia and aerodynamic asymmetry into consideration.

As the reentry body develops in the direction of slenderization and miniaturization, the possibility of an uncontrolled reentry body having low altitude rolling resonance will grow greater and greater. Therefore, it is significant to study rolling speed control, and adopting active controls such as a mobile motor or a center of gravity adjusting mechanism are ways of avoiding rolling resonance; but one way worthy of more study is the passive controls, i.e. making $\bar{C}_{m0}$ as small as possible through selection of nosetip configuration and ablative meterial, and adjusting wrapping method and spacing of the heat resistance layer for controlling $C_{\ell 0}$ in order to attain the purpose of avoiding rolling resonance.

Although the statistical model for calculating the ablative configuration can perform numerical simulation tests of ablative random nosetip configuration and its slightly asymmetrical aerodynamic forces, the associated factors are difficult to determine accurately due to the extremely complicated process of ablation. Therefore, to solve this problem, it is still necessary to rely on the application of a systematic identification technique to conduct processing of flight test data and analysis of recovered nosetip configuration.

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